



The Argon Fluoride laser as an enabler for low cost inertial fusion energy

ARPA-E FUSION Workshop

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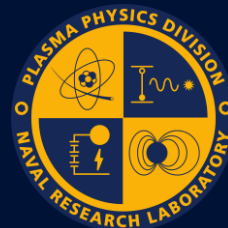
San Francisco Airport Marriott Waterfront

Presented by Stephen Obenschain

Laser Plasma Branch

Plasma Physics Division

Work supported by DOE-NNSA and NRL 6.1



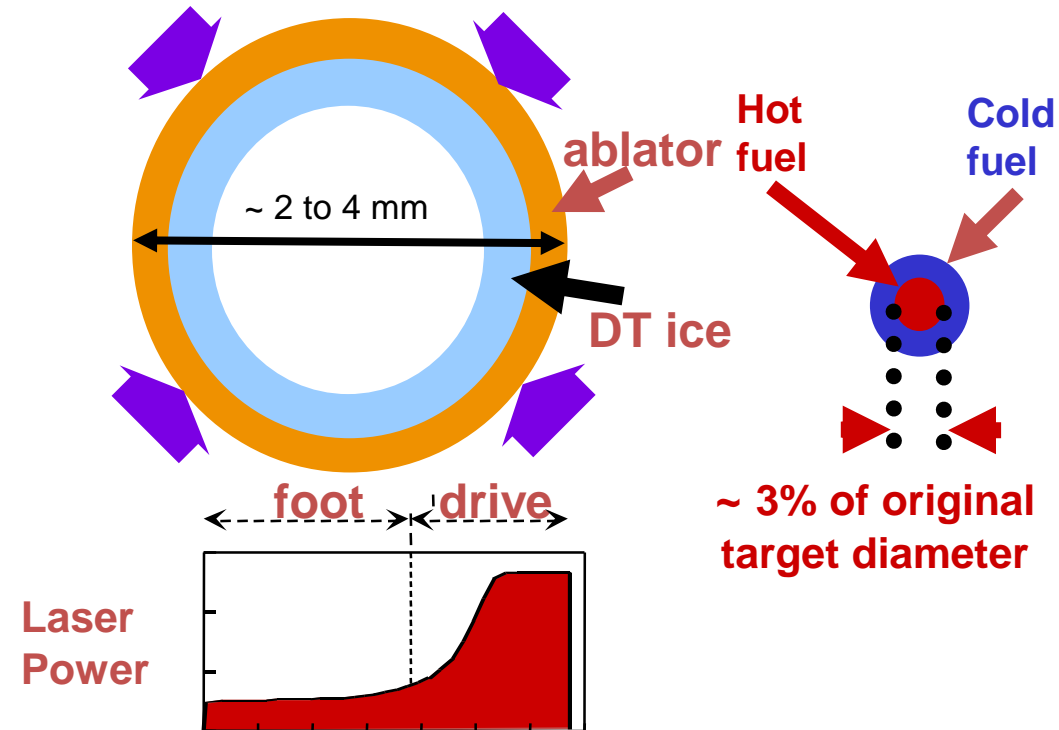
Why an ArF laser driver could enable lower cost modest size laser IFE power plants

The superior laser target coupling with ArF's deep UV light (193 nm) could enable the high target gains needed for the energy application at much lower laser energies than previously thought feasible. The combination of deep UV light and broad native bandwidth (>5 THz) suppresses laser-plasma instabilities that limit the laser intensity and ablation pressures of current 351 nm frequency-tripled glass lasers which are the traditional laser drivers for fusion. ArF is a potentially disruptive technology for laser fusion that shares several advantageous technologies with the krypton fluoride (KrF) laser technology ($\lambda=248$ nm) used on the Nike laser system located at the Naval Research Laboratory (NRL). The ArF laser would utilize similar electron-beam pumping to that used for large KrF amplifiers. It would also be able to use the beam smoothing technology demonstrated on Nike that enables very uniform illumination of directly driven targets and provides the capability to “zoom” the focal profile to follow an imploding target. The KrF technology was chosen for the Nike facility because of numerous advantages for achieving laser fusion. ArF laser light in turn would be superior to KrF. For the IFE application, kinetics simulations indicate that ArF would have as much as 1.6x higher intrinsic efficiency than KrF. The advantages would enable the development of modest size and low cost power plant modules utilizing laser energies well below 1 MJ. This would drastically change the present view on inertial fusion energy (IFE) as being too expensive and the power plant size too large.

Inertial Fusion (via central ignition)

Lasers or x-rays heat outside of pellet, imploding fuel to velocities of ~ 300 km/sec

Central portion of DT (spark plug) heats to ignition.



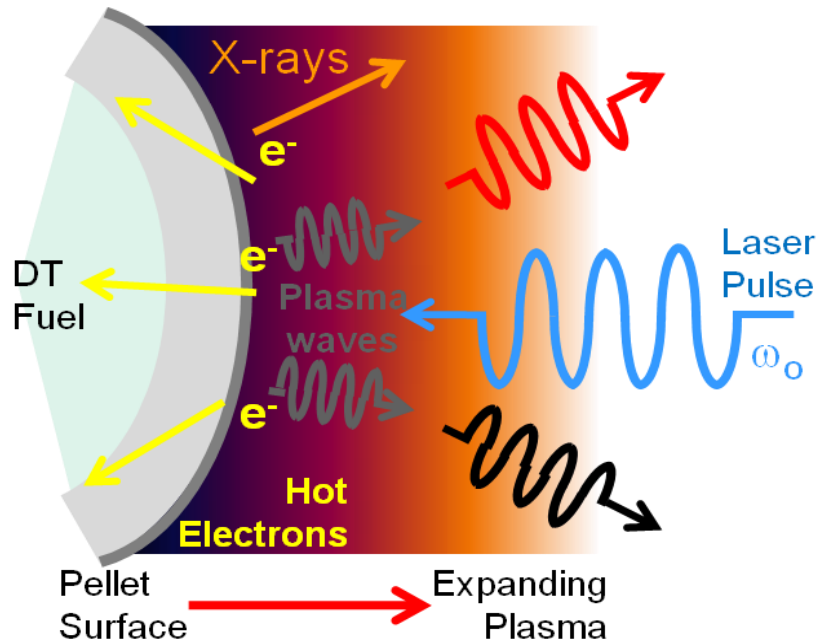
Thermonuclear burn then propagates outward to the compressed DT fuel.



- Simple concept
- Potential for very high energy gains
- Requires high precision in physics & systems
- Need to understand & mitigate instabilities

Laser plasma instabilities (LPI) cause problems for ICF/IFE

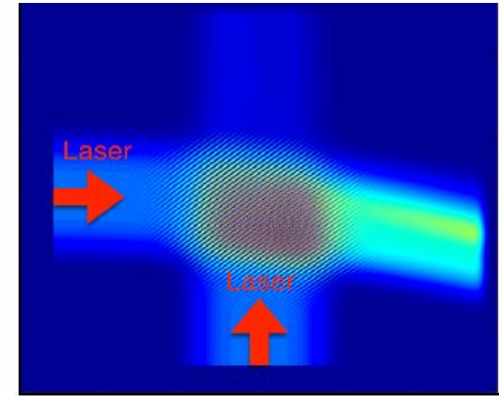
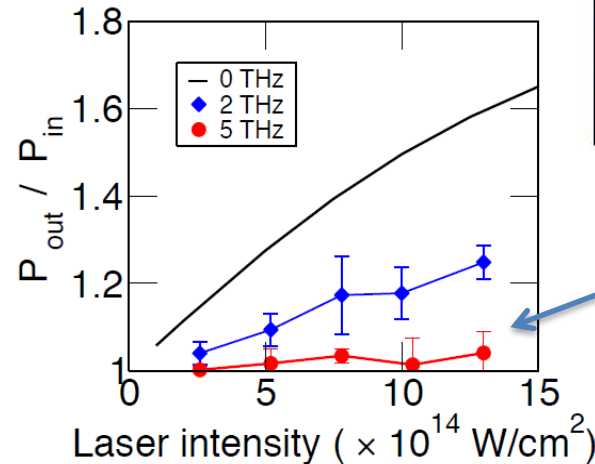
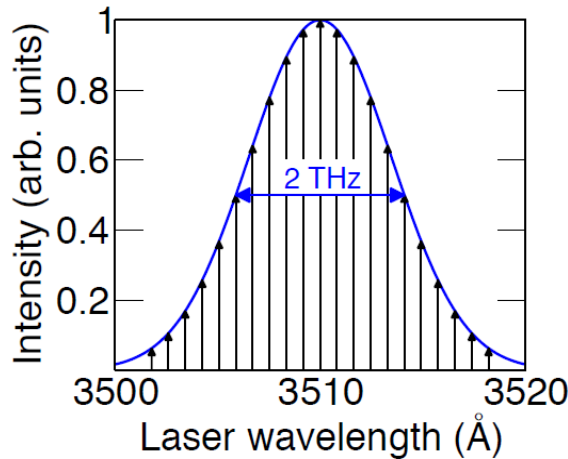
- LPI produced high energy electrons can preheat target impeding its compression.
- LPI induced scattering reduces laser drive and can spoil symmetry.
- LPI limits the maximum usable laser intensity and ablation pressure



- Short laser wavelength increases the instability intensity thresholds
- Broad laser bandwidth can disrupt the coherent wave-wave interactions that produce LPI

Simulations utilizing LLE's LPSE code indicate cross beam energy transport (CBET) can be suppressed with broad laser bandwidth

Simulations show that 2 THz bandwidth produced by discrete randomly phased lines begins to mitigate CBET, while 5 THz has a large effect. **The ArF laser should easily provide > 5 THz bandwidths on target**

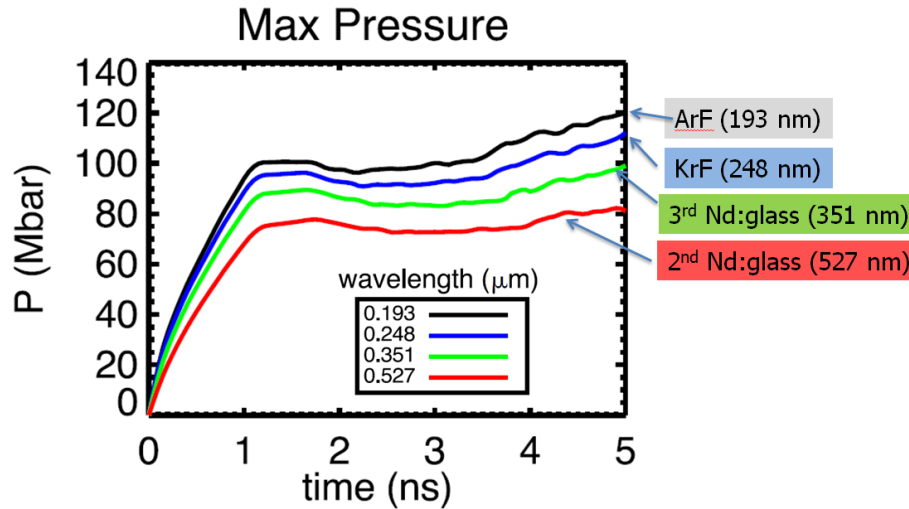


CBET almost eliminated with 5 THz bandwidth

Mitigation of cross-beam energy transfer in inertial-confinement-fusion plasmas with enhanced laser bandwidth, J. W. Bates, J. F. Myatt, J. G. Shaw, R. K. Follett, J. L. Weaver, R. H. Lehmborg, and S. P. Obenschain, Phys. Rev. E 97, 061202(R) – Published 18 June 2018. <https://journals.aps.org/pre/abstract/10.1103/PhysRevE.97.061202>

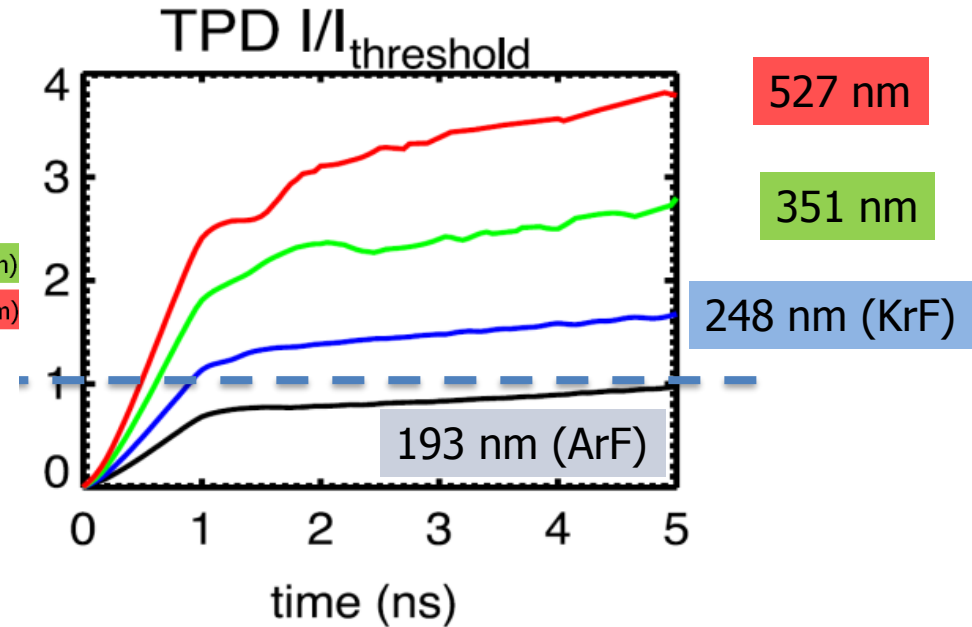
Deeper UV light improves hydro efficiency and increases LPI thresholds

Ablation pressure vs laser λ from hydrocode
 10^{15} W/cm² 2.6 mm solid CH sphere



Direct drive ablation pressure increase's with shorter laser wavelength

TPD thresholds vs laser λ from hydrocode
 10^{15} W/cm² 2.6 mm solid CH sphere

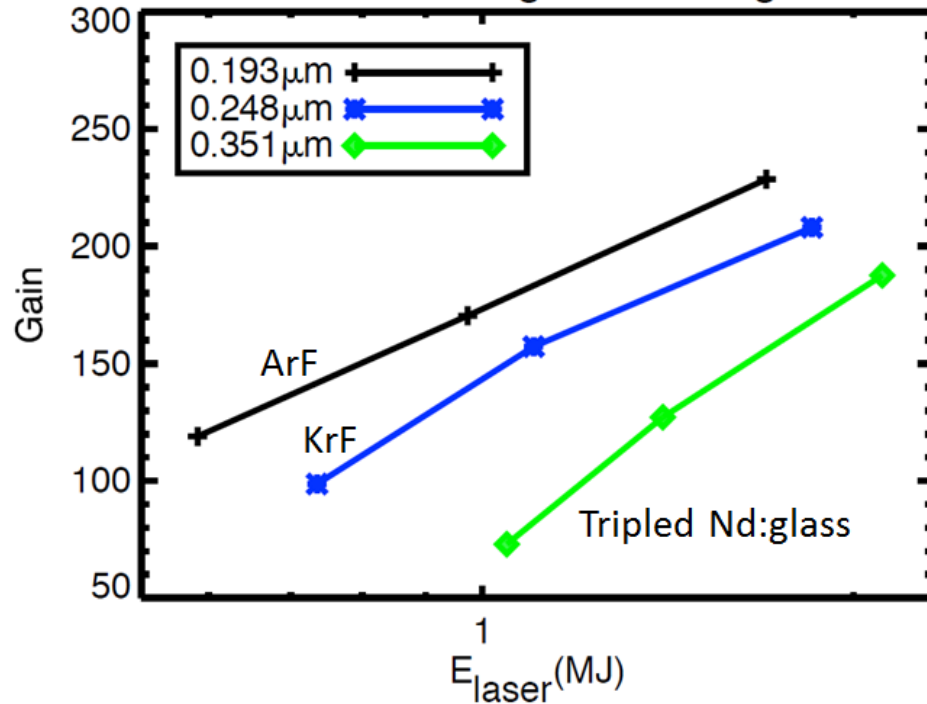


In this simulation one remains below the TBD threshold with 193 nm light

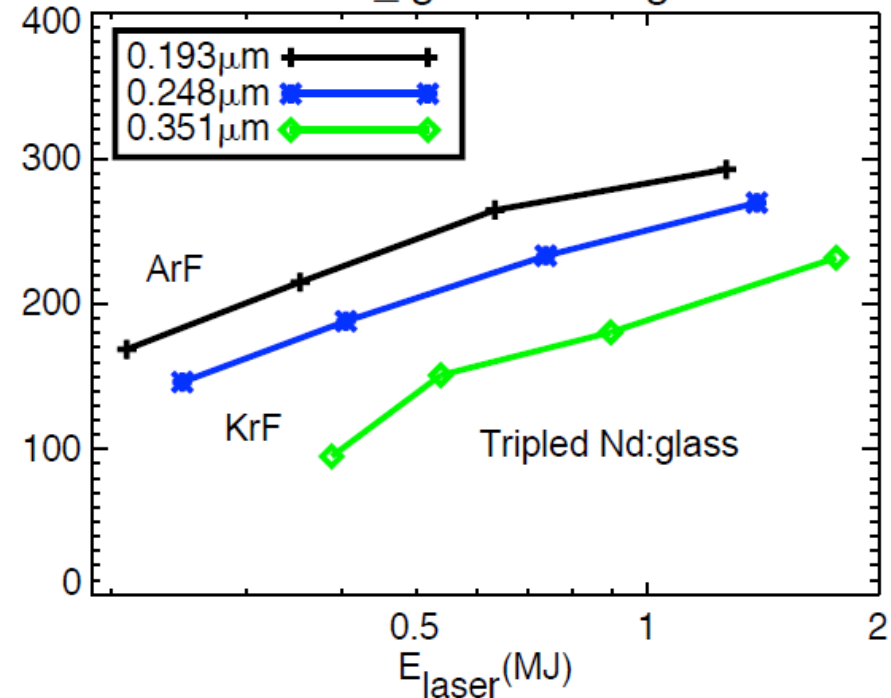
NRL FAST radiation hydrocode 1-dimensional simulations of the gain of conventional and shock ignition^{1,2} direct-drive implosions for ArF, KrF and a frequency tripled glass laser.



Conventional Ignition Designs



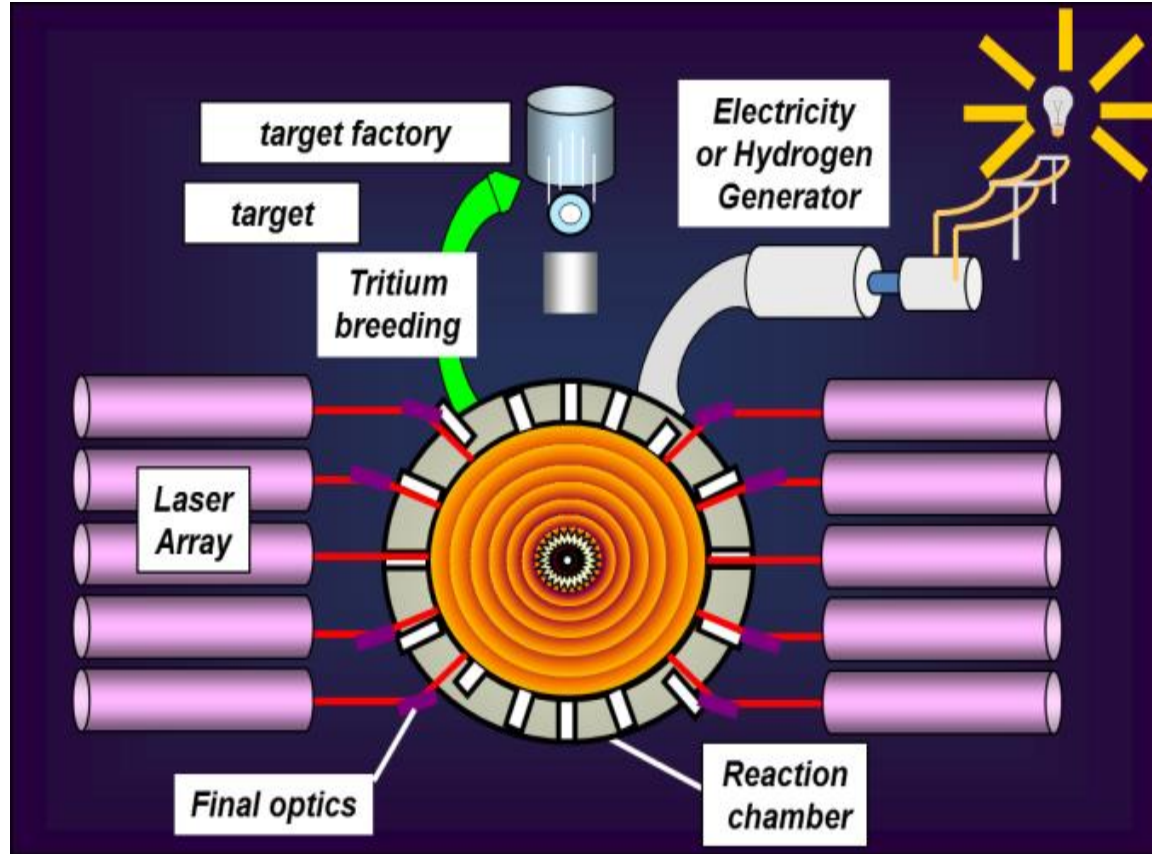
Shock_Ignition Designs



1. R. Betti, C.D. Zhou, K.S. Anderson, L.J. Perkins, W. Theobald, A.A. Solodov, Phys. Rev. Lett. 98 (2007) 155001.

4 Simulations of high-gain shock-ignited inertial-confinement-fusion implosions using less than 1 MJ of direct KrF-laser energy, Jason W. Bates, Andrew J. Schmitt, David E. Fyfe, Steve P. Obenshain, Steve T. Zalesak, High Energy Density Physics 6 (2010) 128–134

Key Parts of a Laser Inertial Fusion Energy Power Plant



Operation at 5 to 10 pulses per second.

Pellets containing frozen or liquid DT fuel are injected and engaged by multiple laser beams.

Reaction chamber ID is ~10 meters.

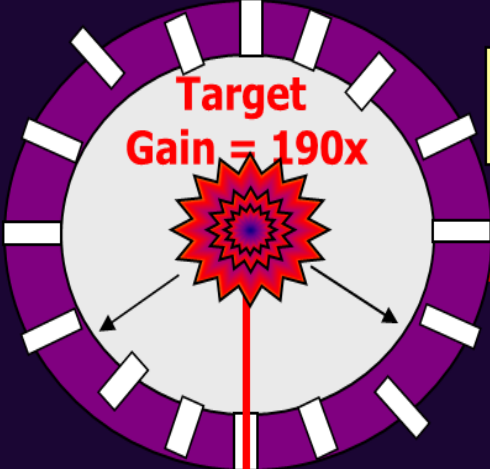
Lithium containing “blanket” in the walls breed tritium.

Major components are modular and separable

Diagram of the energy flow of a laser fusion power plant using a 10% efficient 0.5 MJ ArF laser system operating at 10 Hz. and a 190x gain shock ignited target. The large product of laser efficiency times energy gain allows most of the produced electricity to be distributed to the grid.

Target "Gain" = Fusion power OUT / laser power IN

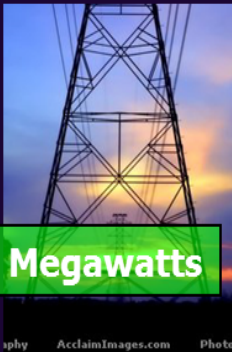
(Nuclear reactions in chamber "blanket" add 1.1× to target gain)



**1045 Megawatts
(heat)**

**Electricity
Generator
(40%)**

**418 Megawatts
(electricity)**



368 Megawatts

Power Lines

50 Megawatts

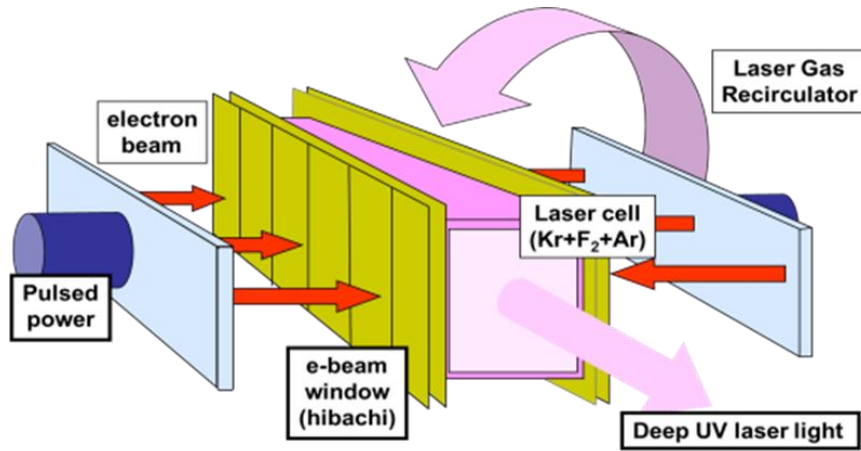
**ArF Laser
10% efficient)**

**5 Megawatts
(0.5MJ @ 10Hz)**

start here

50/418 = 12%
Recirculating power

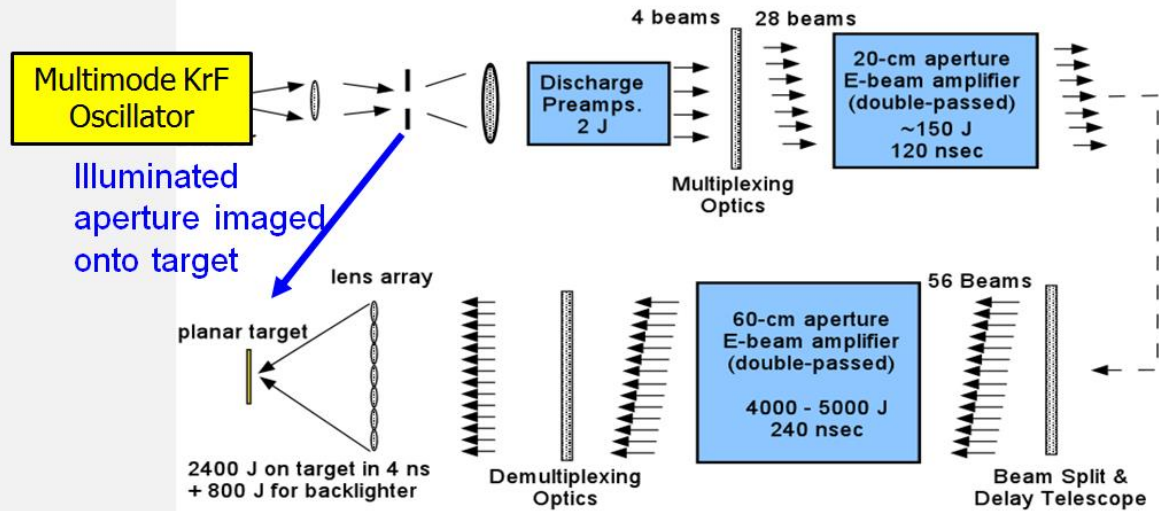
KrF and ArF excimer laser drivers are attractive driver candidates for ICF – deep UV and broad native bandwidth



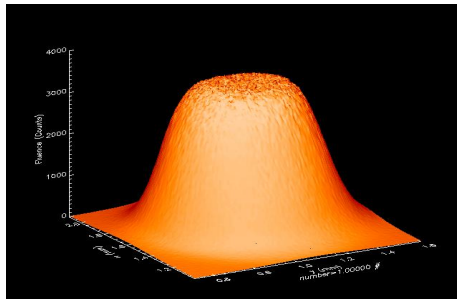
Nike 60-cm aperture KrF amplifier

- Gas laser (easier to cool enabling faster shot rate)
- Electron beam pumping for large amplifiers
- The NRL Nike 3-kJ KrF system (248 nm with up to 3 THz bandwidth) has operated for 24 years
- Electra KrF system demonstrated 5 pulses per second operation for hours
- The deeper UV (193 nm) and broader native bandwidth ArF laser would provide still better light for ICF

Excimer angularly multiplexed laser optical systems provide high target illumination uniformity and easy implementation of focal zooming

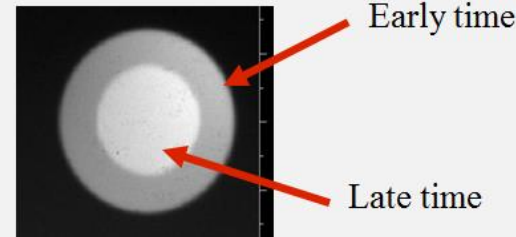


Nike KrF optical system with ISI smoothing
An ArF system would be similar



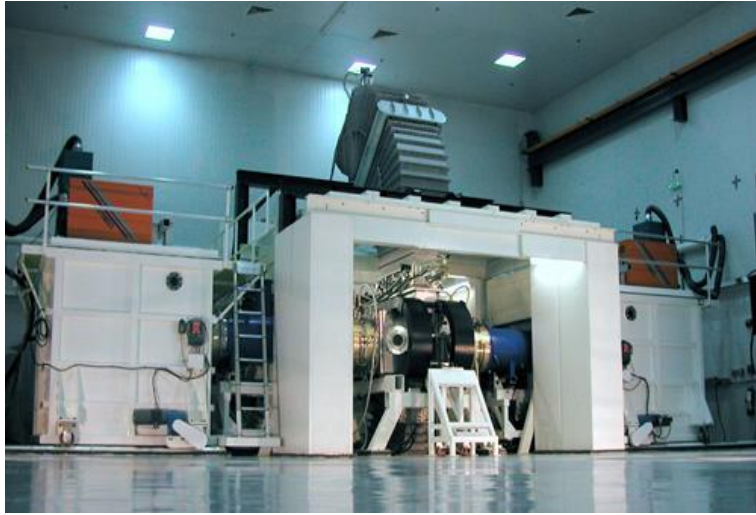
Time averaged laser spatial profile in target chamber

Nike zoomed focus:



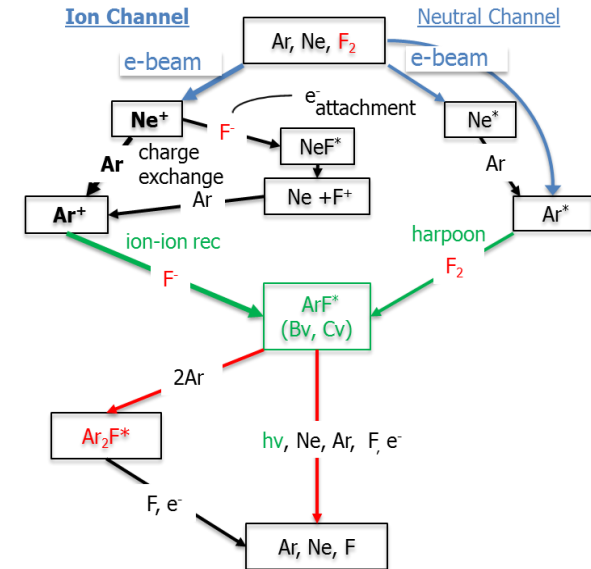
NRL 6.1 funded effort is advancing the basic physics of E-beam pumped ArF laser using the Electra facility

Parametric experimental studies on Electra



Modify & validate
NRL Orestes
laser kinetics
model for ArF

ArF theory and simulations



Notes

- ArF can utilize electron-beam pumping developed for KrF
- But details are different – lower gain and higher saturation flux
- ArF lithographic industry has developed durable 193 nm optics – need to be scaled up in size for ICF

Path forward for developing S&T for IFE using an ArF laser driver.

Tasks consistent with APRPA-E mandates

- Modify the Electra amplifier to be optimized for ArF operation (higher current, lower voltage), to verify NRL codes for ArF laser performance.
- Develop and test lower cost more compact high-repetition rate pulse power – applicable to both ArF and other fusion concepts. A conceptual design has been done by NRL for a 700kV, 100ns, 1 Ohm module with >10⁸ pulse life at 10Hz. It has less than half the number of silicon thyristor stacks and capacitors required in alternate approaches such as a hypothetical solid state Linear Transformer Driver (LTD).
- Develop ArF optimized amplifier and system designs using simulations, test where feasible.
- Work with vendors to advance high-power long-lived ArF optics
- Conduct 2-D and 3-D simulations of ArF target designs to determine minimum laser energy needed for robust performance.
- Develop target designs optimized for tritium recovery and recycling

Phased development path to IFE power plants using an ArF driver – parallel target physics and IFE technology efforts

Phase I

Advance basic E-beam pumped ArF laser S&T
Develop/evaluate high energy ArF architecture designs
Evaluate potential for robust high fusion yield/high-gain ArF direct drive implosions via simulations

A-OK



Phase II

Design and build high energy (~ 20 kJ) ArF beamline(s)
LPI/hydro experiments with above to check ArF laser-matter interactions
Develop design for a 0.5 to 1 MJ class implosion facility

A-OK



Phase III

- Design and build ~ 0.5 to 1 MJ implosion facility
- High scientific rep rate (many shots per day) for experiments
- ***Demonstrate the robust high-energy gain implosions needed for IFE***



AOK

Develop and test S&T for IFE application

- Efficient high rep-rate (~ 10 Hz) driver operation
- Low cost targets, target injection & engagement
- Long lived chambers and optics
- Economical system designs

AOK



Inertial Fusion Test Facility

Power plant prototype to test materials and components



Build Fusion Power plants

- [High-energy krypton fluoride lasers for inertial fusion](https://www.osapublishing.org/ao/abstract.cfm?uri=ao-54-31-f103), Stephen Obenschain, Robert Lehmberg, David Kehne, Frank Hegeler, Matthew Wolford, John Sethian, James Weaver, and Max Karasik, Applied Optics, Vol. 54, Issue 31, pp. F103-F122 (2015).
<https://www.osapublishing.org/ao/abstract.cfm?uri=ao-54-31-f103>
- [Spectral and far-field broadening due to stimulated rotational Raman scattering driven by the Nike krypton fluoride laser](https://www.osapublishing.org/ao/abstract.cfm?uri=ao-56-31-8618), James Weaver, Robert Lehmberg, Stephen Obenschain, David Kehne, and Matthew Wolford, Applied Optics, Vol. 56, Issue 31, pp. 8618-8631 (2017). <https://www.osapublishing.org/ao/abstract.cfm?uri=ao-56-31-8618>
- [Mitigation of cross-beam energy transfer in inertial-confinement-fusion plasmas with enhanced laser bandwidth](https://journals.aps.org/pre/abstract/10.1103/PhysRevE.97.061202), J. W. Bates, J. F. Myatt, J. G. Shaw, R. K. Follett, J. L. Weaver, R. H. Lehmberg, and S. P. Obenschain, Phys. Rev. E 97, 061202(R) – Published 18 June 2018. <https://journals.aps.org/pre/abstract/10.1103/PhysRevE.97.061202>
- [Production of radical species by electron beam deposition in an ArF* lasing medium](https://aip.scitation.org/doi/10.1063/1.4995224), G. M. Petrov, M. F. Wolford, Tz. B. Petrova, J. L. Giuliani, and S. P. Obenschain, Journal of Applied Physics 122, 133301 (2017);
<https://aip.scitation.org/doi/10.1063/1.4995224>
- J. D. Sethian and 87 other authors, "The Science and Technologies for Fusion Energy With Lasers and Direct-Drive Targets, IEEE Trans on Plasma Science 38, 690-703 (2010).
- *Science and technologies that would advance high-performance direct-drive laser fusion*, S. P. Obenschain et al. white paper submitted to the Nat. Acad. 2020 Decadal Study of Plasma Phys.: #41 in submitted papers.
http://sites.nationalacademies.org/bpa/bpa_188502.